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A Multi-Criteria Decision Framework for Optimal Augmentation of Transmission Grid – Addressing a Tool for Sensitive Zone Detection in Electricity Market

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A Multi-Criteria Decision Framework for Optimal Augmentation of Transmission Grid – Addressing a Tool for Sensitive Zone Detection in Electricity Market

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Abstract

Transmission system structure has an essential effect on the reliability of the power system and electricity market performance, especially when producers bid strategically. As part of on-going research on the design of a robust algorithm for expansion planning of the transmission grid in the Australian electricity market, this paper presents a framework which addresses: (1) the security of power delivery to the load points of the transmission system in case of single line outages; (2) the minimization of transmission system lost load; (3) an efficient electricity market for market participants; (4) construction and maintenance costs of transmission augmentation options; and (5) operation efficiency of the transmission grid.

The suggested algorithm benefits from the dynamic programming and sensitivity analysis approaches along with the aggregation method in its multi-criteria decision-making to locate the optimum configuration of a future transmission system. A set of indices, which account for impacts of the augmentation options of the transmission grid on five aforementioned reliability and market criteria, are proposed and used in the optimum framework for expansion planning of the transmission grid.

Although the methodology is promising for expansion planning of the transmission system, considering the sensitivity analysis concept employed, the proposed methodology would be suitable to detect the sensitive areas of the transmission system to be expanded. The tool would be very useful in the case of large scale power systems for a smart reduction of the transmission expansion options.

The proposed methodology has been applied to a 6-bus and a modified IEEE 30-bus test system to show the effectiveness of the sensitivity-based algorithm.

KEYWORDS: sensitivity analysis, reliability, electricity market, planning, dynamic programming, linear programming, single contingency

1. INTRODUCTION

The liberalization of the electricity market and the accompanying breakup of formerly vertically integrated companies into different independent enterprises have faced the power-network planner to the new tasks and objectives in the planning of their network. Transmission system as the major part of the electricity market is not exempt of the extreme changes in the operation and planning criteria. Transmission system providers have their own planning criteria based on the electricity market operation and independent system operator policies in serving distribution companies and large loads connected to the transmission grid. These criteria are so variable, ranging from voltage stability issues in the Queensland Transmission Grid, Australia [1] to the Market based issues in California electricity market [2]. However, in-depth analyzing of the transmission planning procedures all over the world can reveal many common points, which have been addressed through most of the implemented industrial schemes.

Although a variety of approaches have been proposed to plan a transmission network in a traditionally vertical integrated power industry [3], it is still necessary to study how to plan the transmission expansion of the independent transmission companies in the market environment. The research publications on this area fall into two broad categories, namely,

A. Adapting prevailing tools for expansion planning of the transmission system in competitive electricity market [4],[5], and
B. Developing new tools for addressing new issues in expansion planning of the transmission system in the new competitive environment [6], [7].

This paper proposes a framework for expansion planning of transmission system in restructured electricity market. The reliability of the transmission system is modeled in terms of Value of Lost Load (VoLL). Single contingency has been considered through definition of an effective index called Contingency Index (CI) and the efficiency of transmission system is measured by the Transmission Usage Index (TUI). Effect of transmission system on the electricity market is evaluated by the Congestion Cost Index (CCI). Finally, the cost of option of transmission expansion is included in the Option Performance Index (OPI), which scores different alternatives of expansion.

The selection is based on the finding of the marginal value for introduced indices with respect to change in topology of the transmission system and rating of transmission lines. This considers sensitivity analysis in finding marginal value for assessment indices. Dynamic programming concept would be used for step by step forward upgrading of the existing transmission system.

The paper is organized as follows. In section 2 the expansion framework based on sensitivity analysis and dynamic programming is presented in detail. The mathematical modeling of the single-sided pool-based electricity market is presented. The set of indices that account for the value of the re-enforcing of the candidate lines in terms of the market efficiency, transmission system reliability and security, and efficiency of the transmission system are presented. Accommodating sensitivity analysis and dynamic programming approaches in the proposed framework makes it a very promising approach for detection of zones of the transmission system for defining expansion options. This method is very appreciable in the case of large scale power systems.

The proposed framework is applied on a 6-bus transmission system along with the modified IEEE 30-bus transmission system; the results of this application are discussed in section 3. A sample of zone detection based on the proposed framework is presented by applying on the modified IEEE 30-bus test system.

Concluded remarks are drawn through section four which closes this paper.

2. THE DYNAMIC SENSITIVITY ANALYSIS FRAMEWORK FOR TRANSMISSION PLANNING

The first step in the expansion planning of a transmission system is the definition of the reference electricity market. The reference electricity market is based on the National Electricity Market (NEM) in the states of Queensland, New South Wales, Victoria, South Australia, Australian Capital Territory, and Tasmania, which is a pool based and double-sided electricity market. The NEM is operating based on the offers submitted by the generators, loads, and merchant transmission network providers.

Generators submit their offers to the National Electricity Market Management Company (NEMMCO) as the Independent System Operator of the NEM. NEMMCO dispatches generators based on the forecasted load of each state.

Figure 1 shows the procedure for modeling of the NEM which is based on a revised version of the model suggested in [8]. The algorithm presented in Figure 1 is started by providing input data in terms of power system data and bidding strategy of generators. Generators submit their offers to the NEMMCO through their marginal cost functions. Assuming a constant marginal cost function of generators, economic dispatch module takes the forecasted load and dispatches horizon year generators based on the ascending order of marginal cost of generators. DC power flow check the optimum pattern of generation in terms of thermal limit of the transmission lines. If optimum generation pattern could not be supported by the existing transmission system, optimal power flow formulated in Equation (1) will be used.

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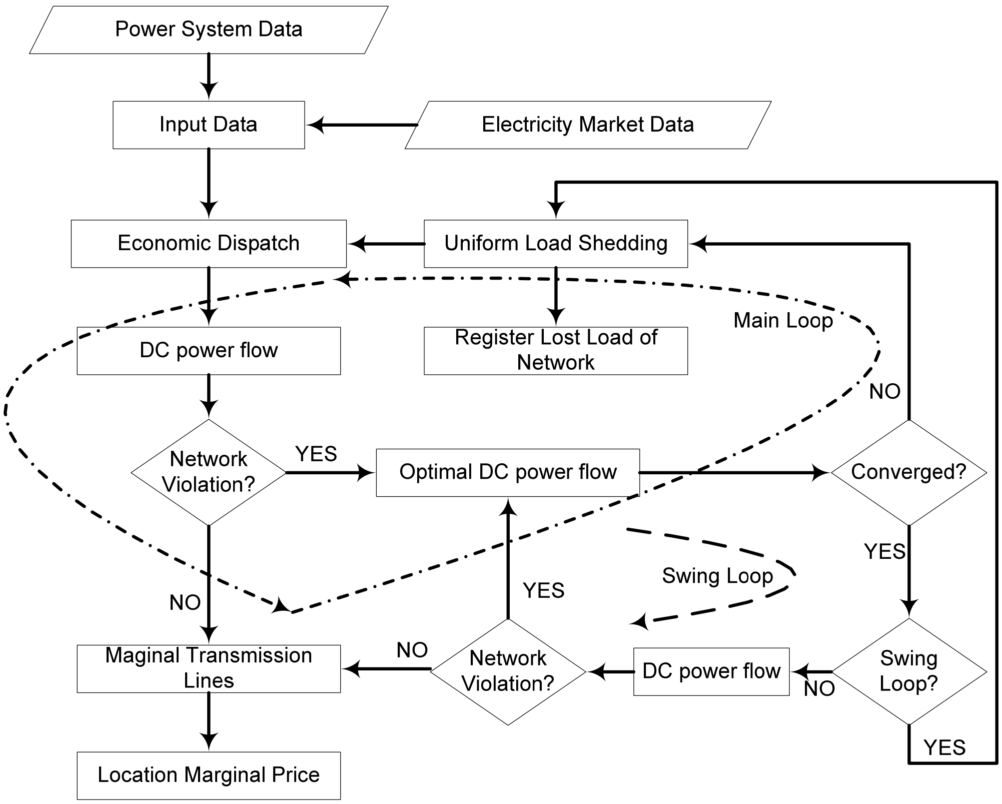

Figure 1 Mathematical Modeling of the One-sided Pool Electricity Market

$$
\begin{aligned}
& Min\sum_{i}^{N_g} MC_{gi}\times P_{gi} \\
& s.t. \\
& \bigcup_{j}^{N_c}\left\langle \sum_{i}^{N_g} GSF_{gi}\times P_{gi} \le \overline{P_{lj}} - \left(P_{lj}^{0} - \sum_{i}^{N_g} GSF_{gi}\times P_{lj}^{0}\right)\right\rangle \qquad (1) \\
& \bigcup_{i}^{N_g}\left\langle P_{gi} \le \overline{P_{gi}} \right\rangle \\
& \sum_{i}^{N_g} P_{gi} = P_d
\end{aligned}
$$

Where in (1), N_g is the number of generators, MC_{gi} is the marginal cost of generator i, P_{gi} is the output active power of generator i, N_c is the number of congested transmission lines, GSF_{gi} is the generator shift factor of generator i, $\overline{P_{lj}}$ and $\overline{P_{gi}}$ are the upper thermal limit of the line j and generator i, respectively. P_{lj}^{0} is defined as the active power flowing through transmission line j. P_d is the total connected demand to the system.

Given the convergence of the revised simplex method in solving (1), the optimum generation pattern is fed to the DC power flow. If there is no network violation, the optimum dispatched pattern is saved, and the marginal transmission lines are detected. Marginal transmission line is a line which is loaded right at its limit. In case of network violation, swing loop tries to find the optimum generation pattern to serve the connected load. If swing loop is not converged to an optimum generation pattern, connected load to the transmission system will be decreased by a uniform load shedding scheme. The main loop is calculated until a stable power system in terms of thermal limit of transmission lines is found.
When main loop is completed, the marginal transmission lines are found. If there is no marginal transmission line, then the power market will clear at the market clearing price which is the marginal price of the last unit dispatched. All nodes will have the same price.

In case of marginal transmission lines, Locational Marginal Price (LMP) is calculated. LMP is calculated based on the contribution of each horizon year generator in the supporting of 1MW load connected to each bus. Two sets of equations (2) are used for the LMP calculation at each bus k.

$$\begin{aligned} &\bigcup_{j}^{N_{MTL}} \left\langle \sum_{i}^{N_g} GSF_{gi} \times \Delta P_{gi} = GSF_{gk} \right\rangle \\ &\sum_{i}^{N_g} \Delta P_{gi} = 1 \end{aligned} \tag{2}$$

LMP can be found by using the summation of the product of change of each generator by its marginal cost.
At this step, the LMP of each node and lost load of the network resulting from applying the horizon year generators and transmission system are saved.

To achieve a successful topology for transmission system in deregulated environments, it is necessary to define some criteria to measure the value of a specific expansion plan from view points of reliability, security, and operating efficiency of the transmission system as well as the economic efficiency of the electricity market. The following sensitivity indices are used by this paper as the representatives of the major factors in evaluating transmission expansion options.

Reliability is an inherent characteristic and a specific measure of any component, device, or system, which describes its ability to perform its intended function. In the context of power systems, reliability in general terms is related to the degree of assurance in providing the customers with continuous service of satisfactory quality. The term “system reliability” can be grouped into two fundamental aspects of system adequacy and system security. Adequacy is associated with static conditions and does not include system disturbances. On the

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other hand, system security relates to the ability of the system to respond to disturbances arising within the system [9].

As a primary responsibility of the independent transmission company (ITC) in providing a reliable transmission system, the following two sections introduce two sensitivity indices for evaluating of the expansion options of the transmission system from the perspective of adequacy and static security. For the sake of mathematical formulation of the proposed indices, $\overline{X}$ and $\overline{Y}$ represent the state of transmission system and electricity market, respectively. The State of transmission system is defined as the topology of transmission network and connection points of generators and loads along with the technical specification of these components. State of electricity market includes the bidding strategy of generators in terms of their marginal production costs.

This paper defines a comprehensive index, Option performance Index (OPI) to embrace the adequacy, security, and efficiency of transmission system along with the efficiency of the electricity market. This index is the weighted summation of the following indices.

A. Transmission System Adequacy

Adequacy of transmission system can be evaluated based on the total load curtailment of the transmission system. As presented through Figure 1, the main loop is responsible for removing congestion from the system by firstly, redispatching of the committed generators and secondly, load shedding. Each time the shed load is registered, the Value of Lost Load (VoLL) is calculated. For demonstration purposes, the VoLL per MWh is considered as \$1000 which does not resemble those used in actual systems, such as \$10 000/MWh for Australian NEM [10]. Transmission system adequacy Index, TSAI, can be expressed as:

$$TSAI = -\left(\frac{\Delta VoLL(\overline{X})}{VoLL(\overline{X})} \times \frac{1}{INV(\overline{X})}\right)^{\alpha} \tag{3}$$

Where α is an odd empirical coefficient, $\overline{X}$ is the state of the transmission system, $VoLL(\overline{X})$ is the Value of the Lost Load considering $\overline{X}$ as the state of transmission system, and $INV(\overline{X})$ is the value of investment to get the transmission system at the state of $\overline{X}$.

B. Transmission System Static Security

The first step in finding the static security of the transmission system is the contingency monitoring. Line outage distribution factor is used for contingency screening. If A is defined as the set of severe single outages of the transmission system and B is defined as the set of all lines, then

$$A = \{ j \in B \mid P(j) \geq 0.8 P_{Max}(j) \} \tag{4}$$

In (4), j is the line number and P(j) is the active power flowing through the line j. Finally, the Transmission System Static Security Index (TSSI) can be defined as:

$$TSSI = -\left(\frac{\Delta SCI(\overline{X})}{SCI(\overline{X})} \times \frac{1}{INV(\overline{X})} \right)^{\alpha} \tag{5}$$

where in (5), Security Contingency Index can be found through equation (6).

$$SCI(\overline{X}) = \sum_k \omega_k \left(\sum_j \left(\frac{|P_j^k(\overline{X})|}{P_{j,rating}^k} \right) \right)$$
$$\sum_k \omega_k = 1 \quad \omega_k \geq 0 \tag{6}$$

In equation (6), $|P_{jk}|$ is the absolute value of the power flowing through line j given outage of line k, $P^k_{j,rating}$ is the rating of line j, and ω_k is the severity index of the outage of transmission line k, which is evaluated based on the power flowing through line k before outage. j is moving over those transmission lines that have the post outage power flow more than their rating limit. In this sense, the inner summation in (6) has a value more than 1 if there are congested transmission lines. Based on the value of $SCI(\overline{X})$ calculated through (6), (5) can find the influence of a specific expansion on the overall security of the transmission system.

C. Transmission System Operating Efficiency

The operating efficiency of the transmission system can be evaluated through the Transmission System Operating Efficiency Index (TSEI) defined by (7).

$$TSEI = \left(\frac{\Delta SUI(\overline{X})}{SUI(\overline{X})} \times \frac{1}{INV(\overline{X})} \right)^{\alpha}$$
$$SUI(\overline{X}) = \sum_j \left(\frac{|P_j(\overline{X})|}{P_{j,rating}} \right) \tag{7}$$

$|P_j(\overline{X})|$ is the absolute value of the power flowing through transmission line j given the $\overline{X}$ state of the power system. System Usage Index ($SUI(\overline{X})$) is a value

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near to one, with one as the best value. Having calculated $SUI(\overline{X})$, the TSEI can evaluate the effects of a specific expansion option of the transmission system on the overall operating efficiency of the transmission system.

D. Economic Efficiency of the Electricity Market

The Independent System Operator collects more money from the load serving entities than pays to generator owners during the congestion period. It is the inherent nature of the LMP pricing method. On the other hand, congestion in the transmission system could have two effects, namely, preventing market operator from dispatching cheap generators and the introduction of the market power in the system.

Economic Efficiency Index of the Electricity Market, EMEI, can be evaluated based on the transmission system and electricity market states, $\overline{X}$ and $\overline{Y}$, through (8).

$$
\begin{aligned}
EMEI &= -\left(\frac{\Delta CC(\overline{X},\overline{Y})}{CC(\overline{X},\overline{Y})} \times \frac{1}{INV(\overline{X})} \right)^{\alpha} \\
CC(\overline{X},\overline{Y}) &= \sum_{j}^{D} \lambda_j P_{dj} - \sum_{j}^{G} \lambda_j P_{gj} = \sum_{l}^{N} (\lambda_i - \lambda_j) f_l
\end{aligned}
\tag{8}
$$

In (8), P_{dj} is the active power that customer d draws from the connection point j at the marginal price of λ_j, P_{gj} is the active power that producer g injects to the connection point j at the marginal price of λ_j, and f_l is the flow of transmission line l located between nodes i and j. The effect of expansion options on the electricity market can be evaluated by (8).

E. Transmission System Expansion Cost

The function $INV(\overline{X})$ considers the expansion cost of state $\overline{X}$ of the transmission system in all aforementioned indices. This cost can embrace the construction, maintenance, and environmental costs.

Finally, the performance of each expansion option is evaluated based on the Option Performance Index (OPI) defined in (9).

$$
\text{OPI}(\overline{X},\overline{Y}) = \text{W1} \times \text{TSAI}(\overline{X}) + \text{W2} \times \text{TSSI}(\overline{X}) + \text{W3} \times \text{TSEI}(\overline{X}) + \text{W4} \times \text{EMEI}(\overline{X},\overline{Y}) \tag{9}
$$

Where *w* is the empirical weighting factor of each criterion.

According to the principle of the optimality introduced by Bellman and Dreyfus, a policy is optimal if at a stated stage, whatever the preceding decisions may have been, the decisions still to be taken constitute an optimal policy when the result of the previous decision is included.

Applying the theory of Bellman, the optimum state of the transmission system is calculated through a step-by-step augmentation. The general framework of planning is presented in Figure 2. The algorithm starts with the initial options of transmission expansion. It evaluates each option by its comprehensive sensitivity based performance index and then selects the most effective option as the one with the highest value for option performance index. This option is added to the transmission system and deleted from the list of options. This process is continued until a satisfying state for the transmission system is found.

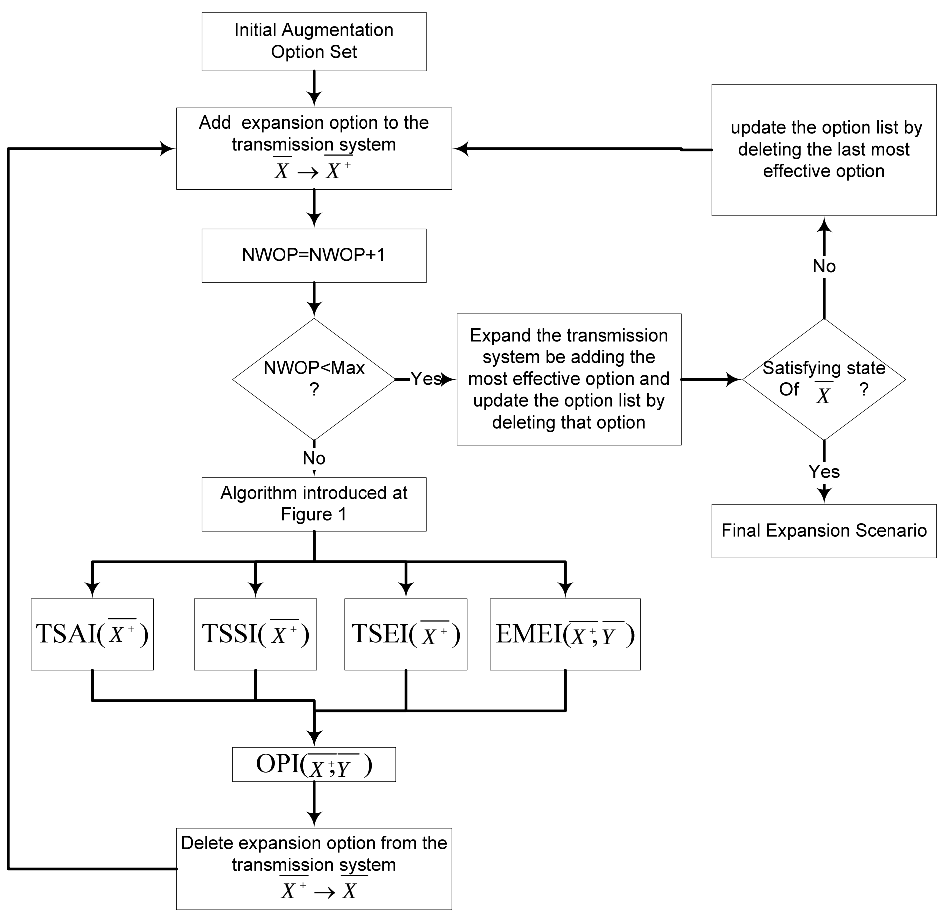

Figure 2 Proposed Sensitivity Analysis Framework for Optimum Expansion Planning of Transmission System using Dynamic Programming

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The next section is involved with the application of the proposed framework on two case studies, namely a 6-bus transmission system and a modified IEEE 30-bus test system.

3. NUMERICAL EXAMPLES

The presented approach is applied to a 6-bus test system. Figure 3 shows the single line diagram of this system.

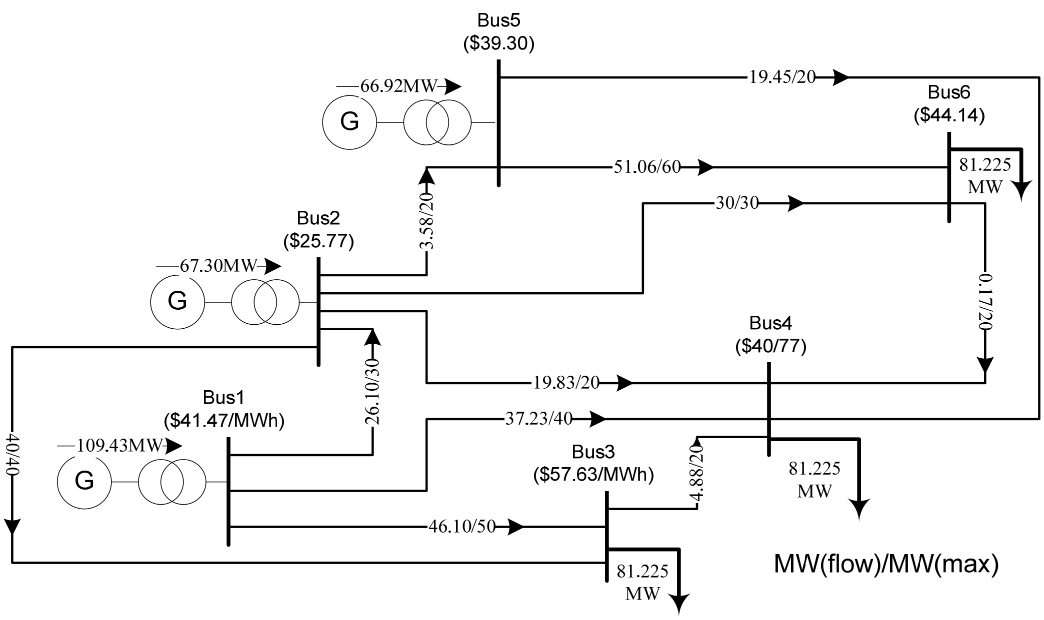

Figure 3 Single line diagram of the 6 bus test system (state of the system before expansion)

Characteristics of generators, transmission lines, and loads for the peak load of horizon year are given in Table 1, 2 and 3. Table 4 summarizes available options for expansion of transmission system.

TABLE 1 DATA OF GENERATORS

Bus No.	Type	Min (p.u.)	Max(p.u.)	Marginal cost* (100$/MWh)
1	Gen.	0.50	2.00	0.4147
2	IPP	0.375	1.50	0.2577
5	IPP	0.45	1.80	0.3930

As it is clear from Figure 3, the transmission system cannot support the total connected load to the system resulting from the lack of capacity. At the operating point of the power system and the electricity market presented in Figure 3, VoLL is $26325/h, SCI is 1.103344 pu, CR is $267567/h and, finally SUI is 0.7244 pu.

TABLE 2 DATA OF THE TRANSMISSION SYSTEM

From	To	R(p.u.)	X(p.u.)	Max Thermal Capacity(p.u.)
1	2	0.10	0.20	0.30
1	3	0.05	0.20	0.50
1	4	0.08	0.30	0.40
2	5	0.05	0.25	0.20
2	3	0.05	0.10	0.40
2	4	0.10	0.30	0.20
2	6	0.07	0.20	0.30
5	4	0.12	0.26	0.20
5	6	0.02	0.10	0.60
3	4	0.20	0.40	0.20
4	6	0.10	0.30	0.20

TABLE 3 DATA OF LOADS

Bus No.	Min (p.u.)	Load (p.u)	Max(p.u)
3	0	0.90	0.90
4	0	0.90	0.90
6	0	0.90	0.90

TABLE 4 DATA OF THE TRANSMISSION EXPANSION OPTIONS

No.	From	To	Right of way	X(p.u.)	Max Thermal Capacity (p.u.)	Cost (p.u.)
1	1	2	3	0.10	0.40	200.00
2	1	3	3	0.14	0.35	150.00
3	1	4	3	0.12	0.38	160.00
4	1	5	3	0.15	0.30	140.00
5	1	6	3	0.18	0.58	130.00
6	2	3	3	0.14	0.35	150.00
7	2	4	3	0.12	0.38	180.00
8	2	5	3	0.10	0.45	250.00
9	2	6	3	0.12	0.38	180.00
10	3	4	3	0.18	0.28	130.00
11	3	5	3	0.18	0.28	135.00
12	3	6	3	0.10	0.45	250.00
13	4	5	3	0.12	0.38	180.00
14	4	6	3	0.10	0.45	250.00
15	5	6	3	0.10	0.40	190.00

Applying the introduced set of indices to the expansion options of the transmission system, TSAI, TSEI, TSSI and EMEI are shown through Figures 4 to 7, respectively. Based on the sensitivity indices obtained, option 10, which is associated with building of one transmission line between nodes 3 and 4, has the highest effect on the overall performance index of the transmission system. The Algorithm selects the option 10 and adds it to the existing transmission system.

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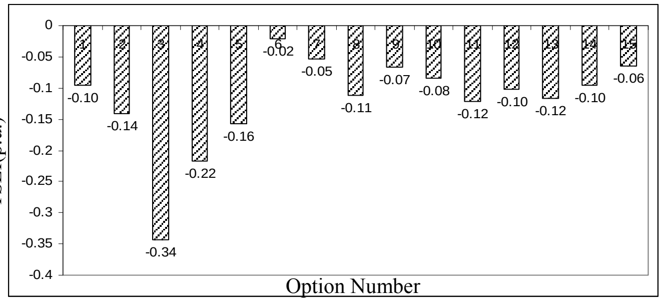

Figure 4 TSEI in p.u. versus 15 expansion options of the transmission system

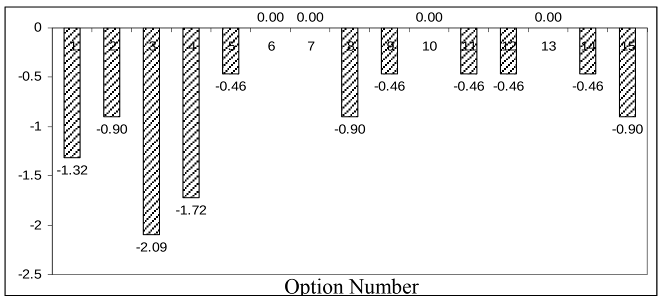

Figure 5 TSAI in p.u. versus 15 expansion option of the transmission system

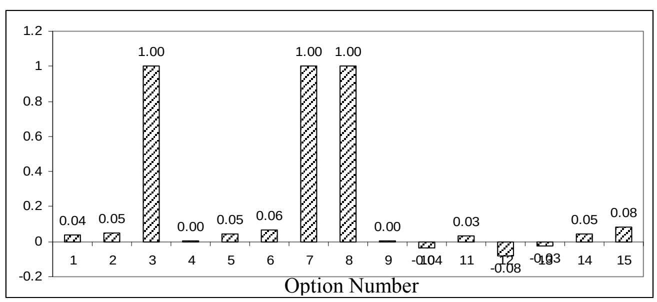

Figure 6 TSSI in p.u. versus 15 expansion option of the transmission system

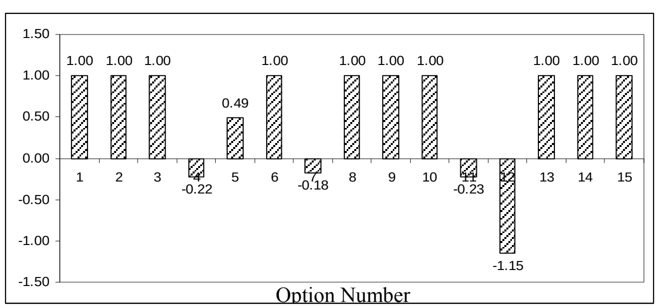

Figure 7 EMEI in p.u. versus 15 expansion options of the transmission system

Figure 8 shows the percentage of the overall performance of the transmission system by addition of each option to the transmission system. As it is clear, the overall performance of the transmission system assessed by OPI is improved by 36% after expansion of the transmission system with option 10. The improvement of the objective function by using the option number 11 as the best option is 92%. The stopping criteria for the algorithm is based on either the available budget for transmission augmentation or the value of OPI ($\overline{X}$, $\overline{Y}$), which does not show any remarkable change after a successful expansion of the transmission system.

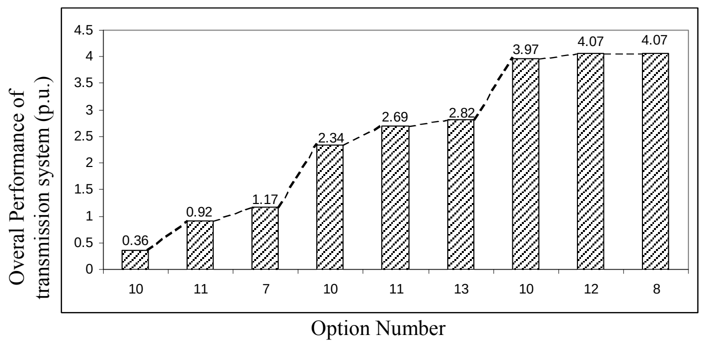

Figure 8 OPI versus selected options for final augmentation of the transmission system

From Figure 8, the set of {10,11,7,10,11,13,10,12} are selected as the best options for expansion of the transmission system. Based on the stopping criterion, no significant improvement is achieved after the addition of option 12. The designed transmission system can serve 270 MW load of the horizon year with \$41.41/MWh as the uniform price of electricity. System Contingency Index is zero with 46% reported as the TUI. Figure 9 presents the state of the transmission system after expansion.

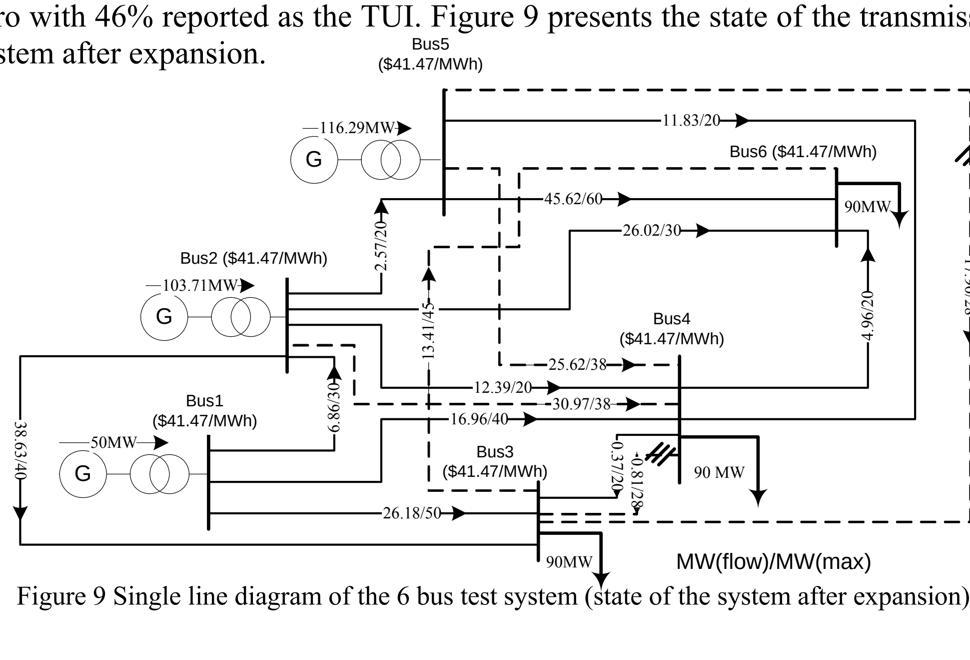

Figure 9 Single line diagram of the 6 bus test system (state of the system after expansion)

A modified IEEE 30-bus test system [5] is used for final evaluation of the proposed planning method. The single line diagram of this test system is shown in Figure 10. The initial state of the transmission system has \$194858.6/h as the VoLL, SCI of 1.22 p.u. and SUI of the 0.464 p.u.

In this case, the set of options {14-19, 16-17, 19-22, and 22-30} are selected as the best options in the planning of the transmission system. The designed transmission system can serve 527 MW load of the horizon year with \$22/MWh as the uniform price of electricity. System Contingency Index is zero with 44.40% reported as the TUI.

As it is clear through the test systems, the sensitivity approach along with the proposed transmission planning framework are able to locate the transmission assets in predictive way to find the quasi optimal solution using dynamic programming concept. As another application of the proposed framework, especially in the case of large scale power systems, the proposed method is able to detect spots with high level of sensitivity to the objectives.

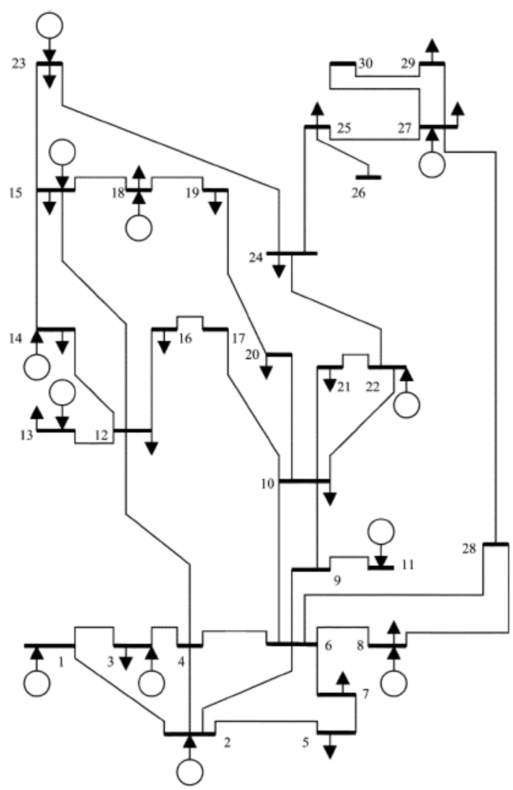

Figure 10 Single line diagram of the modified IEEE 30 bus test system

In this context, the geographical area of the transmission grid is evaluated based on the introduced indices, namely, TSAI, TSSI, TSEI, and EMEI. The areas with high level of sensitivity are detected and used for more inspection in case of the allocation of transmission assets. This method is very appreciable in finding the right spots for the planning and effective reduction of the search space.

Figure 11 shows the application of the methodology in finding the sensitive spots of planning for the modified IEEE test system. A typical dividing of the system into two zones is shown in this figure.

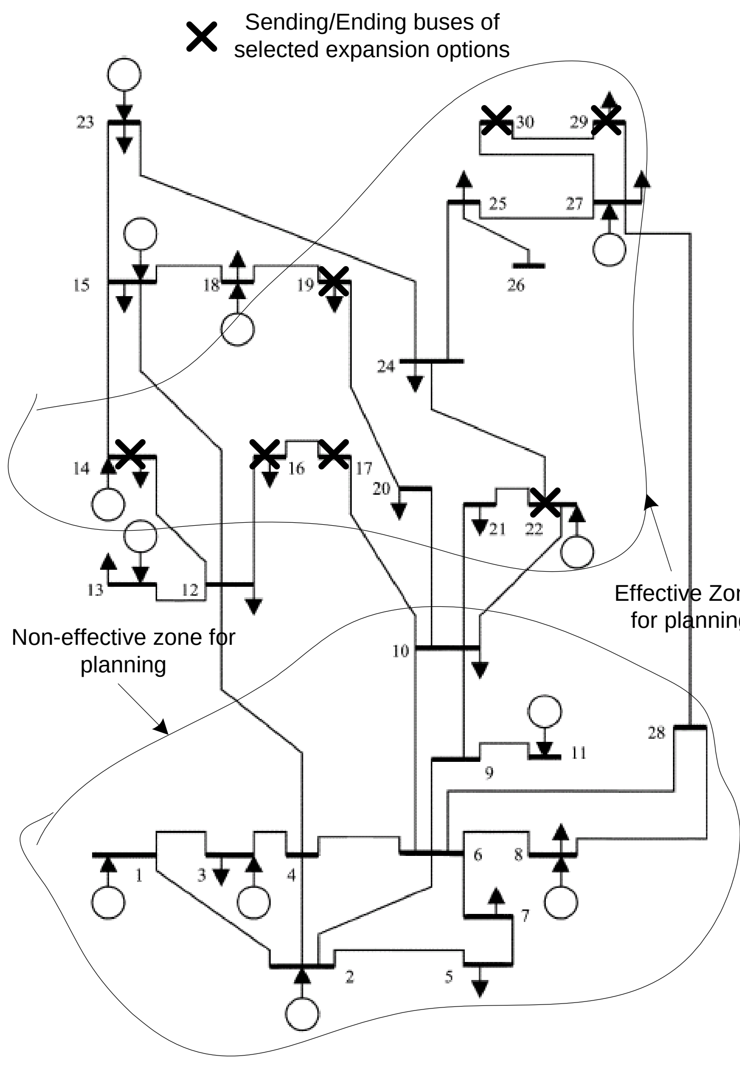

Figure 11 Single line diagram of the modified IEEE 30 bus test system (state of the system after expansion) and sensitive spot detection

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4. CONCLUSION

The transmission planning framework proposed by this paper applies the concept of sensitivity analysis by defining a series of assessment indices and locates the transmission assets using the dynamic programming procedure.

The transmission planning framework accommodates the transmission system adequacy, transmission system static security, transmission system operating efficiency, and transmission system expansion cost in its framework for addressing an efficient transmission system in terms of transmission system reliability and electricity market efficiency as defined in this paper.

The effectiveness of the proposed methodology has been validated by applying it to a 6-bus transmission system and the modified IEEE 30-bus system.

Although, the algorithm is promising enough in expansion planning of the transmission system, the approach is very useful for dividing the transmission system area into different zones based on the effect of each zone on the overall transmission system performance. The areas with the high level of sensitivity evaluated based on the introduced indices, namely, TSAI, TSSI, TSEI, and EMEI would be the best spot for transmission system planning.

In the case of large scale power systems such as Eastern transmission system in Australia, this method is very appreciable in finding the right spots for planning and the effective reduction of the search space.

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